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SUSTAINABLE DEVELOPMENT OF DECOMMISIONED FPSO AS A FLOATING SOLAR PLANT – CASE STUDY OF THE EFFECTS OF TILT ANGLE ON ENERGY EFFICIENCY

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ABSTRACT

Between 1977 and 2017, more than thirty floating production assets were removed, partly due to the high operation & maintenance (O&M) cost. On the other hand, global installations of floating PV have been more than doubled since 2016. Compared with fixed PV systems, floating PV has certain advantages. For instance, seawater can contribute to the cost-effective cooling mechanism of the PV panel. This paper presented a new concept of conveying decommissioned FPSO as a platform for floating PV plant. The proposed PV system is designed to power offshore platforms or drilling rigs. Effects of tilt angle on energy outputs were evaluated through a frequency-domain hydrodynamic analysis of the FPSO. Results showed that roll motion has a larger negative effect on the total radiation on a collector, compared with pitch motion.

Keywords: FPSO; Floating PV; Tilt angle; RAO; Decommissioning; Energy efficiency.

NOMENCLATURE

Abbreviations

FPSO	Floating Production Storage and Offloading
RAO	Response Amplitude Operator
PV	Photovoltaic

Symbols

m	Air Mass Ratio
I_B	Beam Insolation At Earth's Surface
A	Apparent Extraterrestrial Solar Insolation
k	Atmospheric Optical Depth
C	Sky Diffuse Factor
I_{BC}	Beam Insolation On Collector
Σ	Collector Tilt Angle
I_H	Insolation On A Horizontal Surface
I_{DH}	Diffuse Insolation On A Horizontal Surface
I_{DC}	Diffuse Insolation On Collector
I_{RC}	Reflected Insolation On Collector
ρ	Ground Reflectance
I_C	Insolation On Collector
β	Solar Altitude Angle
δ	Solar Declination
φ_S	Solar Azimuth Angle
φ_C	Collector Azimuth Angle
i,j	Member Index
X	Motion Response
ω	Wave Frequency
M	Mass Matrix
AM	Added Mass Matrix
B	Radiation Damping Matrix
K	Hydrostatic Restoring Matrix
F_{ext}^{1}	1^{st} – order Wave Exciting Force

1. INTRODUCTION

A conventional FPSO is a ship-shaped floating system for production, processing, and storage of oil. FPSOs are one of the most widely applied floating platforms in the offshore oil & gas industry, especially for deep-water. Usually, an FPSO is capable of serving an oilfield for over

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20 years. Platform owners need to decide whether the FPSO is going to be decommissioned, driven by the commodity price, O&M cost and basin maturity, etc [1]. Between 1977 and 2017, 36 floating production asset were removed [1]. **Figure 1** shows floating platforms removals categorized by the asset type between 2016 and 2030, for which FPSOs have taken up more than 50% in the total number of removals.

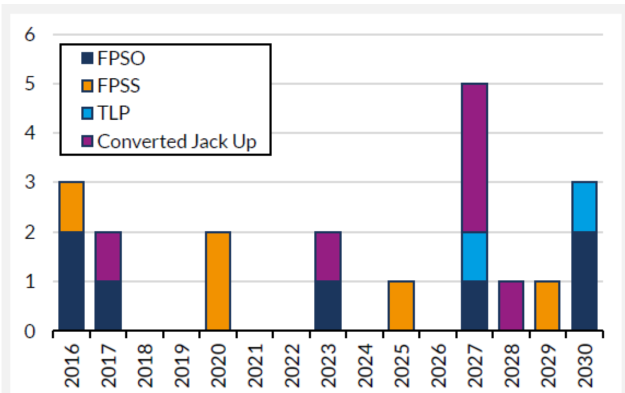

Figure 1 Production Asset Removals by Asset Type [1]

Meanwhile, oil companies are investigating the potential of power offshore platforms by more renewable energies to cut CO_2 emission. Wei, et al showed a theoretical potential of integrating a 20MW wind farm into a stand-alone oil & gas platform grid [2]. Recently, the energy company of Equinor has announced plans to power three platforms by renewable energies, such as wind and solar [3].

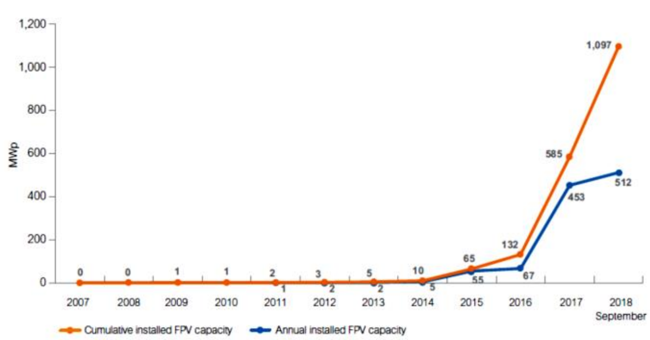

Figure 2 Global installation of floating PV capacity [4]

Global floating PV market has seen a great increase since the past two years. As can be seen from **Figure 2**, the global installed floating PV capacity was more than doubled in 2018 compared with 2016 and the total capacity keeps increasing [4]. Similar to offshore floating structures, platforms of floating PV systems include pontoons or floats. Compared with fixed PV, floating PV systems are new concepts and the design of new floating structures for PV systems has been widely investigated in recent years [5][6][7]. In this paper, a new concept of utilizing decommissioned FPSO as the floating platform for floating PV systems was assessed in terms of the effects of tilt angle.

2. METHODOLOGY

2.1 Clear sky insolation and collector tilt angle

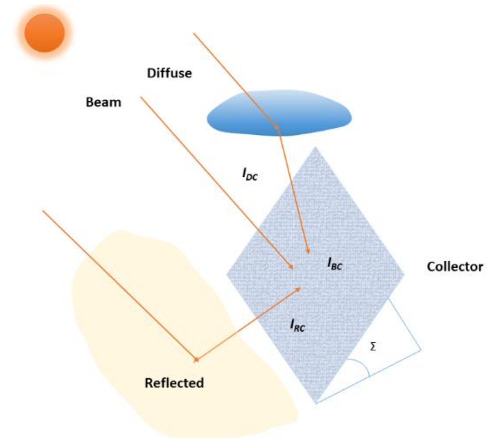

Figure 3 Solar radiation striking a collector and tilt angle, adapted from [8]

Solar collector usually uses a combination of a direct beam, diffuse and reflected radiation, shown in **Figure 3**. Without a tracking system, the total radiation strikes on a collector on a clear day are given by [8]:

$$\mathrm{I_C} = \mathrm{Ae^{-km}}\left[\cos\beta\cos(\Phi_S - \Phi_C)\sin\Sigma + \sin\beta\cos\Sigma + \mathrm{C}\left(\frac{1+\cos\Sigma}{2}\right) + \rho(\sin\beta + \mathrm{C})\left(\frac{1-\cos\Sigma}{2}\right)\right] \quad (1)$$

2.2 *FPSO hydrodynamics in the frequency domain*

Assuming water waves are non-rotational, inviscid and incompressible, hydrodynamics of the FPSO is solved based on the potential flow theory. Numerical solution of the governing equation is realized through a boundary element method in the frequency domain under different wave periods. In frequency domain analysis, the wave field is divided into the diffracted wave and radiated wave, respectively.

After solving the wave exciting forces, added mass and radiation damping, the displacement RAO can be evaluated by the following frequency domain equation for a range of frequencies:

$$\sum_{j=1}^{6}\left[-\omega^2\left(\mathrm{M_{ij}} + AM_{\mathrm{ij}}\right) + \mathrm{i}\omega\mathrm{B_{ij}} + \mathrm{K_{ij}}\right]\mathrm{X} = \mathrm{F_{ext}^1} \quad (2)$$

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3. INFLUENCE OF TILT ANGLE ON ENERGY EFFICIENCY

3.1 Turret-moored FPSO

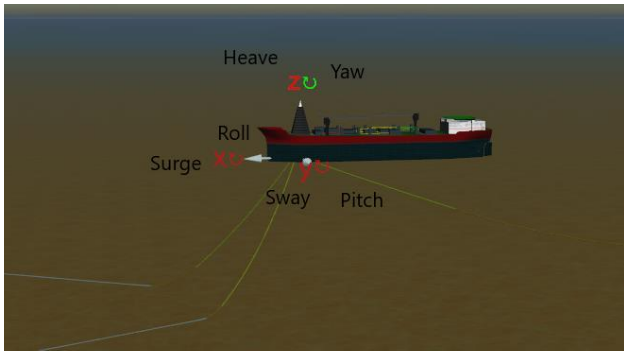

Figure 4 FPSO 6-DOF motion responses and definition of the coordinate system [9]

Station-keeping systems of FPSOs include spread moorings, turret moorings, detachable moorings, and dynamic positioning, etc. A turret moored FPSO (see **Figure 4**) is considered in this paper, which is one of the most widely applied offshore assets. A turret-moored FPSO has a single point mooring system whose moorings have the capability of the weathervane. For example, the turret enables an FPSO to rotate freely in a combination of wind, wave, and current loading conditions. The six DOF motion responses of an FPSO is displayed in **Figure 4**. There are three translational motions (surge, sway and heave) in parallel with the coordinates x, y, and z, respectively, while the rotational motions around the three coordinated are roll, pitch, and yaw, respectively.

3.2 Effects of pitch and roll motion

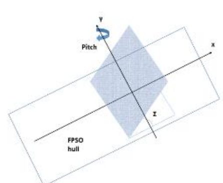

Figure 5a Case study 1: location and orientation of the PV panel, effects of pitch motion, top view

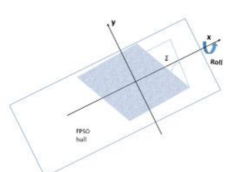

Figure 5b Case study 2: location and orientation of the PV panel, effects of roll motion, top view

Total radiation on a collector is studied using two case studies, as shown in **Figure 5**. Case study 1 assumes that the PV panel is rotating around the y-axis (see **Figure 5a**). Under this assumption, the major contributing factor on the tilt angle comes from the pitch motion. Similar assumptions were applied to case study 2 where the effect of the tilt angle is related to the FPSO's roll motion (see **Figure 5b**).

Table 1 A, k and C for the 21st Day of Each Month [8]

Month:	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A (W/m^2):	1230	1215	1186	1136	1104	1088	1085	1107	1151	1192	1221	1233
k:	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C:	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Figures 6a and **7a** show pitch and roll RAOs for a ship length of 103 m [9]. In equation (1), the panel had an azimuth angle of 20° towards the southeast. The location of the FPSO is chosen in the North Sea, resulting in a Latitude of 56.511°. Using the solar declination for the 21st of June [8], the solar attitude angle β is 56.889°. Further details on A, k and C in June can be found in **Table 1**. Ordinary ground is assumed, resulting in ρ= 0.2. Applying an initial tilt angle of 52°, after calculating the RAOs, together with equation (1), the relationship between the totally clear sky radiation on a PV panel and a range of incident wave frequencies are shown in **Figures 6b** and **7b**. It can be concluded that both pitch and roll motion has an effect on the total radiation on the collector. Both of them have a minimum amount of radiation at wave periods of nine second. The effects of pitch and roll motions on the total radiation are negligible at extremely low or high frequencies, mainly due to the motion amplitude of the FPSO at these frequencies. Roll motion has a larger influence than pitch motion. Total radiation dropped 11% when wave frequency reached nine seconds in case study 2, while for case study 1, the total radiation dropped is around 2%. In this case, the location of the PV panel in case study 1 is recommended.

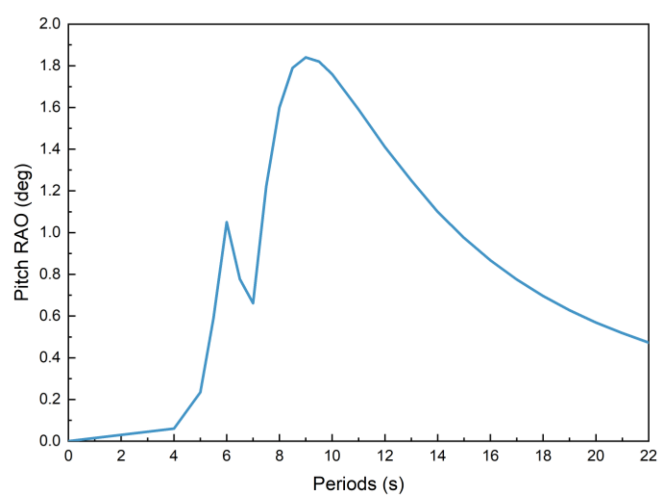

Figure 6a Pitch RAO [9]

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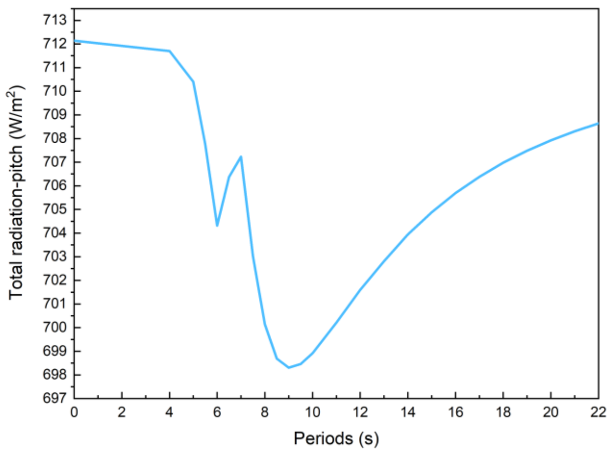

Figure 6b Effect of pitch angle on the total radiation

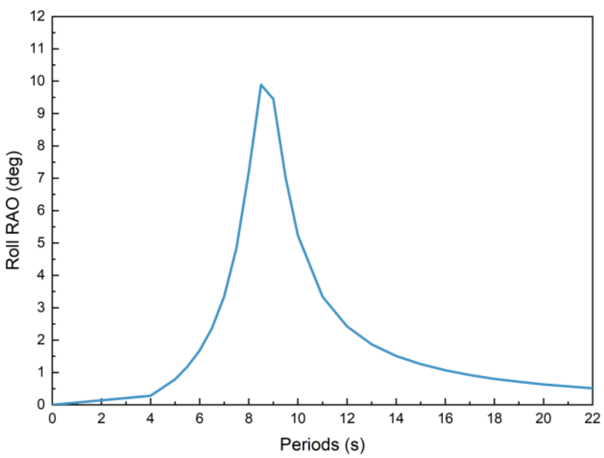

Figure 7a Roll RAO [9]

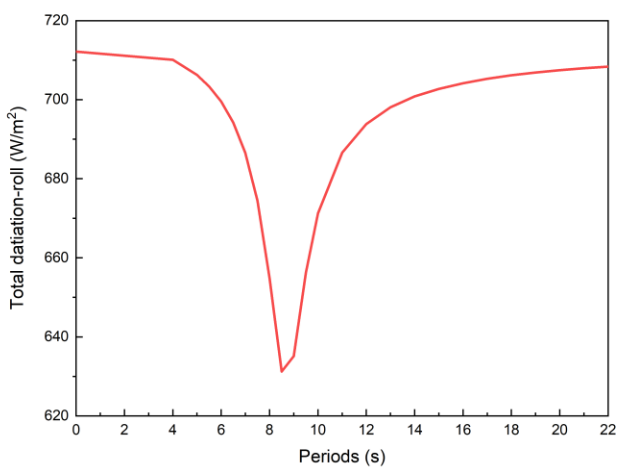

Figure 7b Effect of the roll angle on the total radiation

4. CONCLUSIONS

This paper showed a new concept of utilizing decommissioned FPSO as a platform for floating PV systems. The proposed structure, driven by cutting the CO_2 emission in the offshore industry, is mainly designed to power offshore oil & gas platforms and drilling rigs in a stand-alone environment. Results of two case studies shown that roll motion has a larger negative effect, compared with pitch motion. Based on the frequency domain analysis, the location of case study 1 is recommended. Real sea states are more complicated, having a combination of wind, wave, and current loading effects. Further study will focus on the time-domain analysis.

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